

LABORATORY FOR
COMPUTER SCIENCE
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ARPA/ONR: Research and development program on
computer systems proposed by MIT
1963.

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PROPOSAL
FOR
A RESEARCH AND DEVELOPMENT PROGRAM
ON
COMPUTER SYSTEMS

TO
THE ADVANCED RESEARCH PROJECTS AGENCY
FROM
THE MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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A - INTRODUCTION

1. National Computer Needs

The nation is facing urgent problems, both military and civilian, in which conclusions must be drawn from, and timely actions must be taken on the basis of very large volumes of data collected from a variety of sources. Problems of this type are involved, for instance, in military command and control, air-traffic control, industrial stock and production control, and information retrieval for military, scientific, and health purposes.

The information-processing aspects of these problems have been particularly frustrating. The initial wave of optimism, resulting from the apparently unlimited logical power of digital computers, was followed by the realization that much more was involved than the construction of larger and faster machines. Similar comments can be made about the use of computers in research.

Computer technology has been progressing by leaps and bounds over the last decade, in terms of reliability, size and cost of components, speed of operation, and ease of assembly. On the other hand, the development of techniques for exploiting computers in non-numerical information processing, and as aids in research and in human problem solving and decision making has been relatively lagging. Specifically, computer systems (including programming aids, operational organization, and input, output, and display equipment) have not yet been developed that are easily and economically accessible, and that are truly flexible and responsive to individual needs, particularly the need for quick, direct response. There is substantial evidence that such computer systems can be developed, and that they will play a much more effective role in supporting and extending human cognitive capabilities.

An "on line" mode of operation in which the individual scientist, problem solver, or decision maker is tightly coupled with a computer system of very large memory and speed appears attractive. It appears even more attractive as we envision the evolution of such a system to provide ready communication with others through machine information retrieval, including the development and use of open data files and public subroutines. On the other hand, in order for any such system to be economically feasible, the machine's memory and processing capacity must be shared simultaneously and independently by many on-line users in such a way as to insure its continuous, efficient exploitation. General purpose, independent, on-line use of computers by a large number of people has not yet been achieved, but it appears feasible on the basis of recent experiments with time sharing of large machines.

2. The role of Universities

The development of computer systems of the type envisioned requires the active participation of people engaged in research, problem solving, and decision making in many areas, to insure that the system will satisfy a variety of significant special requirements. In particular, the experience and suggestions arising from a cooperating community of imaginative users will be critical to the sound evolution of programming aids and terminal equipment.

It is clear that universities can provide an ideal environment for such a development effort, because of the great variety of research and other pertinent activities that naturally flourish on their campuses. Furthermore, universities are excellent test communities for experimenting with the notion of computer systems as public facilities, and in particular with the organization and use of public files and subroutines. Last, and most important, the students educated in the midst of such a research and development effort would provide the necessary manpower for effectively attacking the information processing problems facing the Nation.

It is equally clear, on the other hand, that no university can provide, or should attempt to assemble, the manpower and the production facilities necessary to engineer and manufacture computer systems of the size envisioned. While university-built computers have been milestones in the growth of digital technology, the very special and limited resources of universities

should be focussed in the future on less developed aspects of computer systems. Similarly, the most effective long-term use of these resources in the solution of military problems, is their investment in the generation of new knowledge and techniques through work on scientific and other problems appropriate to universities.

3. Character of the effort needed

The computer systems envisioned above should not be regarded as static aggregates of "hardware" and "software" designed and built to meet pre-determined requirements. Rather, they should be pictured as being in continuous evolution through addition, modification and substitution of parts in response to user experience, new requirements, and new technical developments. As a matter of fact, the users themselves may be regarded as part of the system since their own approach to research and problem solving will have to evolve together with the hardware and software.

Thus, a major research and development effort is required which should eventually involve most major universities and computer manufacturers, and last until computer systems are ready to become intrinsic parts of the organizations they serve. The ultimate goal, as vague as it may be, is clearer than the road leading to it, and the initial steps are likely to be uncertain, and probably controversial. It seems, therefore, advisable to start with a pilot-plant operation at one university, working in close cooperation with a computer manufacturer, for the purpose of generating the experimental evidence necessary to plan a broader-based effort.

The close cooperation between a university and a computer manufacturer appears essential to the success of the effort, and yet fraught with legal and ethical problems. These problems will have to be explored experimentally, just as the technical ones, in the spirit of open minded cooperation.

The Massachusetts Institute of Technology has been a leader in the field of computers and information processing since the pioneering work of Dr. Vannevar Bush on analogue computers. It is now ready to spearhead a new research and development effort in the same field, by undertaking at once the program outlined below.

B - RESEARCH AND DEVELOPMENT PROGRAM

1. Broad objectives

The broad, long-term objective of the program is the evolutionary development of a computer system easily and independently accessible to a large number of people, and truly flexible and responsive to individual needs. An essential part of this objective is the development of improved input, output and display equipment, of programming aids, of public files and subroutines, and of the overall operational organization of the system.

The initial development effort should be regarded as a pilot-plant operation intended to provide the knowledge and the experience necessary to plan a broader program involving an increasing number of universities and other organizations.

A second, concomitant objective is the fuller exploitation of computers as aids to research and education, through the promotion of closer man-machine interaction. This second objective is not only important by itself, but it is also essential to the development of the computer system envisioned above, and vice versa.

The third objective, which must be part of any university activity, is the long range development of national manpower assets through education in the pertinent area; of Faculty as well as of students, and outside M.I.T. as well as within the confines of the campus. Again, this third objective is inextricably interwoven with the preceding two, because people's approach to problems will have to evolve in parallel with the computer hardware and software.

2. Initial computer system

The development of the computer system envisioned above will be by necessity a sort of bootstrap operation. In fact, the evolving system will be, simultaneously, the main research tool and the primary object of experimentation, as well as the tangible product of the development effort. Thus, the point of departure must be an existing computer system, capable of evolving in the desired direction during the initial phase of the program.

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The system most appropriate for this purpose is the one presently available in the M.I.T. Computation Center. It consists of an IBM 7090 computer with provisions for time sharing between four users: three on-line users operating through flexowriter typewriters, and one passive user of the Center's Monitor System. The number of possible on-line users will be increased to 16 by March 1963, and plans have been made for connecting to the system the IBM 1620 computer of the Civil Engineering Department and the PDP-1 computer of the Electrical Engineering Department, to be used as on-line consoles.

Unfortunately, the Computation Center installation is already overloaded, and cannot supply the computer time required by the proposed program. Furthermore, experimentation with the system would be drastically limited by the obligation on the part of the Computation Center to provide continuous service to a large number of users. Thus, it is planned to acquire, as part of the proposed program, a computer system which would in essence duplicate the Computation Center installation, except for the substitution of a 7094 for the 7090 machine.

3. Tentative Program

The character of the long-term program requires that immediate attention be paid to the first three successive steps involved, namely the evolution and exploitation of the initial system, the acquisition of the basic hardware and software for a computer system of substantially greater capacity and speed, and the evolution of such a system in terms of operational organization, programming aids, terminal equipment, etc...The following activities are concerned, in order, with these successive steps.

3.1 Work on initial system. Present plans for research and development on and with the initial computer system amount in essence to extending, speeding up, and integrating work already in progress. With regard to the evolution of the initial system in terms of terminal equipment, the following three projects appear attractive at this time:

a) The PDP-1 computer of the Electrical Engineering Department is a machine designed specifically for on-line operation, and its scope-light pen combination permits very close and convenient man-machine interaction. On the other hand, although its internal operating speed is high, its overall

processing capacity is rather modest. This suggests using this computer as a console, time-sharing the much greater processing capacity of a 7090 or 7094 computer installation.

b) The Civil Engineering Department is presently using an IBM 1620 computer in conjunction with a graphical display unit, as an aid in solving various geometric problems arising in the design of roads. This installation, like the PDP-1 installation, provides convenient man-machine interaction but it has a limited processing capacity. Again, valuable experience could be gained from using it as a console, time sharing a much larger computer.

c) The Electronic System Laboratory and the Mechanical Engineering Department have been cooperating in the development of techniques for machine-aided design. As part of this effort a display console has been designed possessing a number of novel features intended to facilitate the generation and manipulation of graphical information. The actual construction of this console and its connection to the initial system would provide a terminal eminently suited for man-machine graphical communication.

These specific projects are parts of research efforts in progress or of current interest, which are particularly pertinent to the objectives of this proposal. Some of these research efforts, together with their objectives and motivations are briefly discussed in Appendix 1.

3.2 Acquisition of larger system. The ability of the proposed initial system to evolve in the desired direction is severely restricted by the inherent speed, memory, and structural limitations of the 7094 computer. While much valuable experience and information can be gained from the initial system, its organization and overall capacity appear to be inadequate for meeting the objectives of this proposal. Thus, a machine of much greater capacity must be procured at the earliest possible date.

The report of the Long Range Computation Study Group of M.I.T. (dated April, 1961) attached to this proposal as Appendix 2, outlines the specifications of a computer system capable of meeting most of M.I.T.'s needs a few years hence, and discusses various procurement alternatives. This report, and the feasibility of the computer system recommended, were discussed with representatives of several computer manufacturers during the late Spring and Summer 1961. The general reaction was that the computer system envisioned was technically feasible, and could be expected to be operative in about three years.

While this report is somewhat outdated and keyed to a narrower objective than those of this proposal, its conclusions are still very pertinent to the proposed acquisition of a suitable machine.

Having a computer built to M.I.T.'s specifications still appears to be unwise for a variety of reasons, some of which are discussed in the above report. A much more desirable course of action would be to establish a working relation with a computer manufacturer which would make it possible to discuss current machine designs, with the objective of acquiring a prototype, perhaps with minor modifications, of a future machine. The legal and ethical issues involved in such a close working relation would have to be explored in great detail beforehand. A possible procedure for selecting a suitable computer manufacturer might be through the award of two or three study contracts of 3-4 months duration.

It is proposed at this time that a meeting, including some half a dozen people from outside M.I.T., be held as soon as possible for the purpose of discussing the report of the Long Range Computation Study Group, and making recommendations with regard to the acquisition of a machine of considerably greater capacity than the 7094 of the initial system. The meeting should last only two or three days, and be reconvened later on, if necessary.

3.3 Study groups. The procurement of a machine of considerably greater capacity is only part of the next development stage. The planning of terminal consoles, programming aids, and operational organization should also begin as soon as possible. For this purpose, it is proposed to hold through the Spring and Summer 1963 a series of relatively small and short meetings on these aspects of computer system development, in addition to the meeting concerned with the procurement of the machine itself (see 3.2). The series should terminate with a larger two-week meeting with the objective of reviewing the conclusions reached in the whole series of meetings, and making recommendations to M.I.T. and A.R.P.A. with regard to the whole program.

Each meeting will include people from other universities and from industrial and governmental laboratories as well as from M.I.T. Position papers will be prepared and distributed ahead of time as bases for discussion.

The following tentative list of meeting topics indicates the scope and purpose of the series:

a) Meetings on computer system design

Machine structure and procurement
Input-output equipment and display consoles
System organization and operation
Programming languages and aids

b) Meeting on user's requirements

Artificial intelligence and experimental mathematics
Psychology and biophysics
Physics
Engineering design
Economics, management and decision making
Earth sciences
Language processing
Education, including teaching machines

c) Program review meeting

Two-week meeting concerned with the three main objectives of the program, namely computer system development, research, and education.

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C - MODE OF OPERATION

1. Management

The proposed research and development program will require the active participation of members of the Faculty and Research Staff from many M.I.T. Departments and Research Laboratories. Thus, the program will be managed, at least initially, as a special project, operating largely through existing M.I.T. organization.

The project will be directed by Dr. Robert M. Fano, Ford Professor of Engineering. In addition, because of the likely impact of this project on the Institute as a whole, a policy committee has been set up to represent and advise the Institute on matters concerned with the proposed program, and to advise and support Professor Fano in carrying it out. The committee reports to the Provost, Dr. Charles H. Townes, and is presently constituted as follows:

Professor P. M. Morse, Director of the Computation Center, Chairman
Dean G. S. Brown, School of Engineering
Professor P. Elias, Head of the Department of Electrical Engineering
Professor R. M. Fano, ex-officio
Dean G. R. Harrison, School of Science
Professor A. G. Hill, Physics Department
Dean H. W. Johnson, School of Industrial Management
Professor C. F. Overhage, Director of Lincoln Laboratory

2. Research Staff

It is envisioned that the program will eventually involve a rather large number of people from various Academic Departments and Research Laboratories, as indicated by the pertinent current research efforts listed in Appendix 4. The members of the Faculty and Research Staff listed in Appendix 3 have already agreed to devote a substantial fraction of their efforts to the proposed program, and have actively participated in the preparation of this proposal. In addition, it is expected that some 20 graduate research assistants will be involved by Fall 1963.

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It is estimated that the project will require by Fall 1963 additional space for computer installation and staff of the order of 30,000 sq. ft. Various possible locations have been investigated on and in the immediate vicinity of the campus. The only suitable space obtainable by Fall 1963 is located at 545 Technology Square, in a commercial office building scheduled for occupancy in the next few months. The top two floors of the building, amounting to approximately 30,000 sq. ft., have been leased for 20 years by C.E.I.R., which is apparently interested in subletting them for a period of 3-5 years. The terms of such a sublease are presently being negotiated.

D - PERTINENT M.I.T. BACKGROUND

1. Experience with on-line operation

A central objective of the proposed program is to provide flexible, on-line access to computers. Computers specifically designed for flexible, on-line use have been available at M.I.T. for a number of years; the TX-0 computer, built by Lincoln Laboratory, and presently located in the Research Laboratory of Electronics; the TX-2 computer, built by, and located at Lincoln Laboratory, and the PDP-1 computer, a gift of the Digital Equipment Corporation to the Electrical Engineering Department, also located in the Research Laboratory of Electronics. By now, many students, as well as members of the research and academic staff have had the opportunity to use these computers in their work, thereby gaining experience with their exploitation and value as research tools.

2. Long Range Computation Study Group

In late Spring, 1960, a committee was appointed by President Stratton, composed of Professors Fano, Hill, Morse and Wiesner, with Professor Hill as Chairman, for the purpose of formulating a policy with respect to the development of future computer facilities at M.I.T. A Study Group was, in turn, organized to estimate the future computer needs of the M.I.T. community, and to recommend specific means for meeting them. The report of the Long Range Computation Study Group, published in April, 1961, is attached to this proposal as Appendix 2. The conclusions and recommendations of the Study Group were reviewed and accepted by the parent Committee.

The main conclusion of the Study Group was that "The major part of M.I.T.'s computational needs, a few years from now, can best be met by a single very high-speed large-capacity computer system with provisions for time-sharing through a number of remote consoles" and that "this system would be the cheapest way of providing the needed capacity and the only way of providing the necessary, close man-machine interrelationship that we feel is vital for research in the years to come." This conclusion and the system study on which it is based are at the roots of this proposal.

3. Experimentation with time sharing

Experimentation with time sharing has been in progress at the M.I.T. Computation Center for several years. The system^{*} presently in operation,

* F. J. Corbato, M. Merwin-Daggett, R. C. Daley, "An Experimental Time-Sharing System," Proc. of the Spring Joint Computer Conference, May 1962.

as part of the Center's 7090 installation, makes provisions for four independent users. Three of the users can operate on-line through typewriters, while the fourth one consists of programs running in the background through the standard Monitor System. The installation of an additional memory of 32,000 words for storing the time-sharing supervisor, together with other equipment changes, will, by Spring 1963, increase the number of possible independent users to 16.

A time-sharing system has also been designed for the Electrical Engineering Department PDP-1 computer, and will be in operation by Spring, 1963.* This system has provisions for time-sharing eight typewriters, two scopes and light-pens, two tape readers, and two tape punches, as well as one or more real-time control computations through the computer sequence-break system. Initial operation will be with two typewriters, one scope and light pen, and one tape reader and punch.

4. The role of computers in research and education

The role of computers in research and education at M.I.T. is discussed in detail in Sec. B(pp.14-26) of the report of the Long Range Computation Study Group, attached to this proposal as Appendix 2. The survey of computer usage on which this discussion is based was conducted during the second half of 1960.

In early December, 1962, a questionnaire was sent to some 60 members of the Faculty and of the senior Research Staff to determine their interest in the objectives of this proposal, and the extent and nature of current work pertinent to them. The list of pertinent current research attached to this proposal as Appendix 4 was compiled from their replies. Because of the informality of the survey and of the time limitations involved, this list is bound to be incomplete, and somewhat inaccurate. Yet, it provides a clear indication of the strong interest and support that the proposed program can be expected to elicit from the M.I.T. community.

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* J. E. Yates, "A Time-Sharing System for the PDP-1 Computer," Report AFCRL-62-519 (MIT Report ESL-R-140), June 1962, OTS/ASTIA No. AD-285851.

5. Educational program

A significant indication of the extent to which computer and computer related disciplines have spread their roots at M.I.T. can be found in their rapidly increasing incorporation into the subjects of instruction offered throughout the Institute.

A simple measure of this phenomenon is provided by the curves in Appendix 5, obtained by counting the subjects whose description in the M.I.T. Catalogue either mentions computers explicitly, or mentions related disciplines, such as system analysis and information theory, but without reference to computers. The selection criteria employed are subjective but consistent throughout. Thus, the general shapes of the curves are more meaningful than the actual values. The subjects selected from the 1962-63 catalogue are listed in the same appendix to illustrate the criteria employed. The total number of instructors in charge of these subjects is 93, which amounts to approximately 11 % of the M.I.T. Faculty.

Appendix 1 - Research Areas of Current Interest

Programming Languages

An essential feature of any man-machine problem solving system is a powerful, flexible, and expressive language facility. There are a great many specialized programming languages in use today, but most of them are quite restrictive, both in areas of application and ease of expression. While it is possible to conceive of creating a large time-sharing computer system by merely providing a built-in executive routine and scheduling system so that each of the separate programming systems can operate independently and unchanged, such an approach is highly inefficient and poses many problems of compatibility. Furthermore, such an approach offers little in the exploitation of the unique capabilities for new problem-solving techniques which real-time, time-sharing makes possible.

Recent advances in the theoretical foundations of language mechanisms indicate that algorithms can be written which will permit the use of specialized programming languages whose richness approaches that of natural language. The physical form of the languages is of little importance -- the same algorithms will translate verbal or graphical languages of almost any form. The incorporation of semantics as well as syntax into the theoretical structure also will permit generalized operators to be used, so that such features as symbol manipulation can be included in a natural way. The language algorithms are highly efficient and well-suited to multi-processor, multi-user time-sharing system operations. Since each user may build up his own vocabulary, and incorporate in his own fashion, any problem-statement and symbol manipulation features he requires, a system built in this way will have much greater capability than is presently available. Further theoretical research, with reduction of these new developments to practice, is expected to yield working systems for general use in the MIT time-sharing project as well as in computer-aided design.

Computer-aided design

Computers have been used for some time in the engineering field for performing calculations difficult or repetitive enough to warrant the programming time required. There is considerable interest and effort at

the present time in elevating the status of the computer from a "glorified desk calculator" to an active real-time partner to a man in solving many types of engineering problems. For example, work is now underway to extend the Automatically Programmed Tool System (a problem-oriented language used off-line to translate engineering drawings into a form suitable for automatic calculation of machine-tool tapes for numerical manufacturing) into a Computer-Aided Design System, wherein the designer would use the computer on-line to develop and refine all the specifications of a mechanical part or assembly, including shape, weight, strength, choice of standard catalog parts, etc. In the civil engineering field, there is interest in similar extensions of problem-oriented languages now used for solving geometric problems in surveying, design of highways, etc. However, a major limitation in computers which has slowed such applications to date has been the lack of convenient and flexible means for on-line man-machine communication, particularly in the area of graphical and picture languages, which are a primary language form for engineering applications. It now appears that the oscilloscope and light-pen combination can be further developed to provide the necessary facility. Particular problems to be solved in designing remote and time-shared consoles for design use include: faster flicker-free displays; inclusion of character and geometric figure generation independent of the main computer, to free up computing time and memory, and ease data-link requirements; and convenient and flexible means for control by means of light-pens, switches, dials, and alpha-numeric keyboards.

System Programming

To develop for any particular computer a general purpose time-sharing system with the critical time-sharing supervisor program, a number of specific system programming areas must be investigated and appropriate techniques explored and developed. These programming techniques are intimately connected with the hardware and should properly be included in the computer design. Critical areas to be investigated are:

1. The interrupting and switching from one program to another within the high-speed memory.
2. The swapping of programs in and out of the high-speed memory.
3. Memory protection and relocation including the data transfers of input-output equipment.

4. The subroutine linkage of user programs with the supervisor, especially in terms of verification of legitimate parameters.
5. The ability to write read-only subroutines for simultaneous use by many user programs.
6. The appropriateness of time-of-day clocks, accounting clocks and interrupt clocks.
7. The ability to handle input-output easily within the supervisor including the assignment and control of devices such as tape units, scopes, disc memories, drum memories.

Other system programming areas which must be developed are:

1. A control language format including easy input typing conventions.
2. General utility inspection programs such as post-mortems, traces, differential dumps, etc., where the user should be able to specify information symbolically.
3. Inter-console and inter-program communication conventions.
4. Coordination techniques of all messages in and out of the user typewriters.
5. Information and program storage and retrieval conventions.
6. Accounting and auditing procedures for monitoring system usage.

In the area of reliability there must be programmed provision for:

1. The systematic investigation of suspected main computer malfunction without unnecessary system shutdown.
2. Notification procedures for system failures and shutdowns.
3. Development of a gradation of backup procedures and calculated losses for the inevitable mishaps which can occur to any computer system.

Conducting experiments with on-line computation

In many research applications the computer is used as a sophisticated data processing device in which the data sources are experiments being carried out in research laboratories. Some salient examples are nuclear physics experiments with high energy particle accelerators, direct observation of the behavior of animal nervous systems, and the evaluation of psychophysical experiments. Numerous other possibilities await adequate computation facilities for serious exploitation.

At present, it is generally necessary to record data during the experiment, and process it later when computer time is available. Not only does this require expensive equipment or tedious transcription, but the delay in processing and presenting results is frustrating to the experimenter. Frequently, the processed data, if immediately available, would enable the experimenter to change the conditions of the experiment to obtain more significant data. In many cases the computer can even serve to control the conduct of an experiment with more accuracy and precision than the human experimenter, and with more flexibility and sophistication than devices he could afford the time and effort to construct.

In some instances, small general purpose computers are used to process such data on-line. However, the character of the processing is quite limited by the capabilities of the equipment being used. One objective of the proposed research will be to determine how the capabilities of a powerful processor can be made available for on-line experimental applications through time-shared operation.

Research in computer-directed instruction

For the past three years a program of research in automatic instruction has been carried on at MIT. The purpose of this program has been to develop a teaching machine which has as many of the desirable characteristics of the human tutor as possible. The program was motivated by the feeling that existing teaching machines did not serve as tutors but rather as drill masters who seem to bore rather than to stimulate the average student. In order to achieve the sophisticated decision making properties of the human tutor, at least partially, it has been necessary to use a logical element with power of a general-purpose computer. Consequently, the research has focussed on how a teaching machine governed by a computer could be made an efficient and stimulating participant in the educational process.

The difficulty of most previous machines was that the program of instruction could not be sufficiently adapted to the capabilities and interests of the student. A student who answered a given question incorrectly a second time was required to repeat the same sequence of instruction. It was decided that one of the design goals for the computer-directed machine would be to have it present to the student, at each stage in a teaching process, instructive material suited to his state of knowledge in the subject and to his innate ability.

Such a computer-directed teaching machine has been built using the IBM 7090 computer at MIT. The output device of the teaching machine is a microfilm reader modified so as to move to a particular frame upon command of the computer. The machine has displayed an ability both to vary its presentation of course material depending upon the past performance of each student, and to change its decision logic as a result of the past performance of all students. Preliminary studies indicate that as many as 2,000 students could be taught different subjects by the computer at the same time, if an appropriate system of remote teaching consoles were operated in a time-sharing mode. This type of operation appears to be economic even at the present time.

In its ultimate development, the computer-directed teaching machine may function not only as an individual tutor but as the controlling element for many of the phases of education. For example, the teaching system may assign outside work for the student, grade his performance on this outside work, and adapt its future outside assignments to the capabilities of the student for unsupervised instruction.

Research on a useful "mathematical assistant" program

Once the time-sharing system is in operation, we believe we can make available to the scientific world a new kind of service -- the Mathematical Assistant Program. This will be a service for combined symbolic and numerical computation. At the user's request, the program will apply selected transformations and manipulations to mathematical expressions inserted at the console. The user's requests may range from simple substitution of variables through expansions in power series, Fourier series, and other rather complex mathematical operations; to applying complex solution methods for, e.g., solving systems of differential equations, solving eigenvalue problems, etc. Of course, everything the system does must be based on programs written into the system, and much work will be required in the construction of the programs themselves, and the devising of a suitable control language. But the effect will be worth many times the effort, we believe. It should open the way to solving more complex analytic problems (in physics and engineering as well as in mathematics) than can be attempted today. It can also serve greatly to increase the mathematical power of the scientists using the system. For in many cases the scientist will need only to know the conditions appropriate for applying

a certain method; he may not need to develop the technical proficiency now required to competently perform a mathematical operation. It is our view that ultimately the mathematical assistant may become one of the most important developments in scientific methodology, opening a form of mathematical competence to scientists in all fields.

Research on heuristic programming

Heuristic programming is the construction of computer programs to solve problems using sophisticated methods of exploration, learning, pattern-recognition, and other information-processing techniques. MIT has already an outstanding record of achievement in this area. The availability of time-sharing methods should make it possible to extend this research into areas which have, up till now, presented forbidding complications. The reason is that it was necessary in the past to program the entire process before one could begin to explore the quality of its performance. This means that it was necessary to write programs for making every decision that the machine might encounter. With the time-sharing system it will be feasible to run programs that contain lacunae, with the missing decision-making capability supplied by the console operator. In this way we can build up complex programs by steps, where in the past we were presented with the task of working out in advance an entire structure of forbidding complexity. From the viewpoint of application as well, the prospects of complex aids to problem-solving seem much more attractive in the new framework. For example, we have developed a reasonably effective program for performing some of the problem tasks connected with Integral Calculus. On the other hand, without time-sharing, any practical use of such a program requires a very large and special effort. We expect to find immediate practical use for the program as soon as the time-sharing system is operating on a large scale.

Operational studies

The trend in large computer systems is toward greater complexity in design and greater parallelism in operation. No large amount of foresight is required to envision computer systems whose memories are shared by several processors and whose processors are used from numerous consoles. These possibilities raise important and interesting operational problems, not unlike the problems found in a busy telephone system or a bustling

job shop. Research on some of these problems is currently in progress at the School of Industrial Management and at the Operations Research Center.

Most attention to date has been on sequencing and priority problems. The priority problem arises when one or more classes of customers in a servicing operation merits some form of preferential treatment. In a time-sharing computer system, for example, users differ in the urgency of their requests, how long they have been waiting for service, and how much additional time they require. These differences should be reflected in the procedures adopted for assigning priorities to the users. The question is, how?

By way of illustration, short requests for time should take precedence over longer requests for time, other things being equal. This contributes to a high overall service efficiency; that is, to low average delay. In practice, however, attending to this objective may cause partially conflicting objectives to suffer. One study underway attempts to balance the conflicting objectives with the help of priority models, phrased in mathematical terms and with economic considerations incorporated.

Management information and decision systems

Computer oriented research at MIT in the area of management and decision making typically has divided into five main headings.

1. Basic research into process-oriented languages and computer system design; also, compiler development.
2. Simulation studies at the levels of individual, firm, industry, and economy.
3. Business games in the areas of marketing, production, and organization.
4. Statistical studies, some of which employ a back-and-forth interplay with the computer.
5. Operations research: analysis of sequencing, priority, mathematical programming, and other decision models.

Recently, there also has been a great amount of interest in the development of future computer systems and their application directly to the management process, particularly to top-level decision making. Envisioned are management information systems which provide top management with timely financial, inventory, marketing, and production data with no

more discomfort or inconvenience than that associated with the placing of a telephone call. Also envisioned are management decision systems whose central elements, in addition to the management decision makers themselves, are computer simulations and mathematical decision models run from time-sharing computer consoles. Several simulation studies currently in progress have this objective as their primary focus.

Symbolic processes

It has been observed that the way a person approaches a problem is strongly influenced by the language available to him -- a well-known example is the approach to multiplication or division using Roman or Arabic numerals. Thus the facilities available in a programming language may be crucial to the successful utilization of a machine. Besides appropriateness, a programming language must also offer convenience, brevity, fluency, legibility, ease of learning and ease of checkout. Much of the naturalness of some programming languages comes from certain intuitively recognizable underlying similarities to English, yet a programming language must be much more restricted than English, partly because of our severely limited ability to mechanize English. These restrictions cause problems to the user, who must be aware of the limitations, yet not too seriously confined by them.

Research is in progress in the theory of programming and into the practical engineering compromises required of successful programming languages.

Longer range research is in progress, in the mechanical translation group, in the areas of the syntax and semantics of English, logic, and the philosophy of language. The aim of this research is to develop a capability in a computer for handling English meaningfully, that is for understanding unrestricted English.

Research in machine structure

Presently available machines are not oriented in their structural design toward multi-user, remote console operation. The relation between processing units and memory, the means of coupling typewriters and display devices to the machine, and the provision of data terminals for real-time interaction with laboratory experiments are subjects that require the evaluation of new ideas. Many concepts of machine organization can be properly evaluated only through operational experience: One must determine how research workers and students utilize and react to a system designed with new concepts, and one must measure the degree to which system components are efficiently used in typical circumstances.

For example, a computer designed with several processing units, each having access to a common pool of modular memory is very attractive as the core of a multi-user system: It promises to provide efficient utilization of a large memory, greater reliability, ease of expansion, and the possibility of temporarily assigning the full use of one processor to a particular user when justified by special needs. The evaluation of this concept requires the construction of such a system and its utilization in an academic environment.

Appendix 3

The following members of the Faculty and Research Staff intend to devote a substantial part of their efforts to the proposed program.

CORBATO, Professor Fernando J(ose), Department of Electrical Engineering and Computation Center, Massachusetts Institute of Technology, Cambridge 39, Massachusetts. PHYSICS. Oakland, California, July 1, 26, m. 62. B.S. California Institute of Technology, 50; U.S.N. 44-46; M.I.T. Computation Center: Research Associate, 1956-59; Assistant Director in charge of Programming Research, 1959-60; Associate Director, 1960-. Associate Professor, Department of Electrical Engineering, 1962-. Tau Beta Pi; Sigma Xi; Physical Society; Asn. Computing Mach., Editorial Board, 1962-; computer programming and applications; molecular and solid state physics.

Professor Corbato's principal professional interest is in the techniques of computer usage. He is presently active in the development of time-sharing systems.

DENNIS, Professor Jack B(onnell), Department of Electrical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts. October 13, 1931, Elizabeth, New Jersey. S.B., S.M., 1954; Sc.D., 1958 (Electrical Engineering) M.I.T. Teaching Assistant, 1954, Research Assistant 1955, Instructor 1958, Assistant Professor 1959, M.I.T. Fields of interest: Speech communications research; Computer structure for experimental computation; Mathematical programming.

FANO, Professor Robert M(ario), Ford Professor of Engineering, Department of Electrical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts. ELECTRICAL ENGINEERING. Torino, Italy, Nov. 11, 17; nat; m.49; c 3. S.B. Mass. Inst. of Tech. 41, Sc.D. (elec. eng.) 47. Asst. elec. eng. Mass. Inst. of Tech. 41-43, instr. 43-44, radiation lab. 44-46, res. assoc., res. lab. of electronics, 46-47. asst. prof. Elec. Communications, 47-51; assoc. prof., 51-56, Prof. 56-61, Ford Prof. of Eng. 1961-; group leader, Lincoln Lab. 51-53, Fel. Inst. Radio Eng; Fel. Am. Acad. Microwave circuit components; network synthesis; transmission of information; theoretical limitations on the broad band matching of arbitrary impedances. Author: Transmission of Information; Electromagnetic Fields, Energy, and Forces (with L. J. Chu and R. B. Adler); Electromagnetic Energy Transmission and Radiation (with R. B. Adler and L. J. Chu).

App.3-a

- FRICK, Dr. Frederick C., A.B. DePauw Univ. 1938, Ph.D.(Psychology) Columbia Univ. 1947. Served in London, OWI, and USAAF during war. Lecturer at Columbia Univ. 1946-47; Instructor, Harvard 1947-40. In 1950 made Chief, Communications Research Div., USAF Human Factors Operations Research Laboratory; in 1954-55 served as Acting Director, Electronics Research Directorate, USAF Cambridge Research Center. Joined MIT Lincoln Laboratory 1955 as Leader of Psychology Group, appointed Associate Head, Information Processing Division 1959. Appointed Division Head in 1960. For the past few years his major research interest has been in the area of automatic speech recognition.
- GREENBERGER, Professor Martin, School of Industrial Management, Massachusetts Institute of Technology, 50 Memorial Drive, Cambridge 39, Mass. APPLIED MATHEMATICS. Elizabeth, New Jersey, Nov. 30, 31; m. 59. A.B., Harvard, 55, Nat. Sci. Found. fel. 55-56, A.M., 56, Ph.D. (Applied Mathematics), 58. Mgr. appl. sci., Int. Bus. Mach. Corp., 57-58; asst. prof. Indust. Mgt. Mass. Inst. of Tech., 58-61, Assoc. Prof., 61-; Consult., ops. eval. group, U. S. Dept. Navy, 60-; USAF, 52-54, Capt. Ops. Res. Soc.; Asn. Computing Mach.; Inst. Mgt. Sci. Application of the computer and mathematical methods to economic; industrial and management problems; simulation of economic systems; quantitative methods. 'Notes on a new pseudo-random number generator' (J. Asn. Computing Mach.); co-auth., "Microanalysis of Socioeconomic Systems"; ed, "Management and the Computer of the Future."
- HUFFMAN, Professor David A(lbert), Department of Electrical Engineering, Massachusetts Institute of Technology, Cambridge, Mass. ELECTRICAL ENGINEERING. Alliance, Ohio, Aug. 9, 25. B.E.E., Ohio State, 44, M.S.E. 49; Sc.D. Mass. Inst. Tech., 53. Instr. elec. eng. and res. assoc., univ. res. found., Ohio State, 46-50; asst. prof. Elec. Eng., Mass. Inst. Tech., 50-57, Assoc. Prof., 57-62, Prof., 62-; Levy medal, Franklin Inst., 55. USNR, 44-46. Inst. Radio Eng. Fellow 62-; consult. for President's Sci. Adv. Comm. 1959-; Air Force Sci. Adv. Board 1959-62. ~~Switching circuit techniques; automata and information theory.~~
- MINSKY, Professor Marvin L(ee), Department of Electrical Engineering, Massachusetts Institute of Technology, Cambridge, Mass. New York City; Aug. 9, 27. B.A. Harvard 1950, M.S. Princeton, Ph.D. Princeton, 1954 (Mathematics). Junior Fellow, Harvard Soc. Fellows 1954-57, Staff Member Lincoln Lab. 1957-58, Asst. Prof. Math. 58-61, Assoc. Prof. Elec. Eng. 62-; Staff member RLE, MIT Computation Center. Director MIT Artificial Intelligence Group. Editor: J.A.C.M. Member I.R.E., AMA, AAS, NYAS, Sigma Xi, Areas of Interest: Heuristic Programming, Artificial Intelligence, theories and brain function, recursive function theory, mathematical logic, epistemology.

- ROSS, Douglas T(aylor), Electronic Systems Laboratory, Massachusetts Institute of Technology, Cambridge, Mass. MATHEMATICS. Canton, China, Dec. 21, 29, m. 51. A.B. Cum Laude, Oberlin, 51; S.M., M.I.T., 54. Lecturer, E.E. M.I.T., 60-; Head, Computer Applications Group, Electronic Systems Lab., M.I.T. 1956-; Div. of Sponsored Res. Staff, M.I.T., 1952-. Project Engineer, Computer-aided Design Project, 1959-; Technical Director of following projects: PRE-B-58 Fire Control System Evaluation Programming, 1952-56; Automatically Programmed Tools (APT) System, 1956-1959; Computer-aided Design, 1959-. Outstanding Young Man of Greater Boston Award, 1958. Sigma Xi, Assoc. for Computing Machinery, AAAS. Language theory, programming systems, computation techniques, man-machine communications, numerical control of production processes, artificial intelligence, problem-solving systems.
- SELFRRIDGE, Oliver G., Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Massachusetts. MATHEMATICS, London, U.K., May 10, 26. S.B. M.I.T. 45. Staff, Lincoln Lab., M.I.T. 52-. Consult. for PSAC 59-. Artificial Intell., Computation Techniques, Automata Theory.
- SIMPSON, Dr. Stephen M(ilton) Jr., Department of Geology and Geophysics, Massachusetts Institute of Technology, Cambridge, Mass. GEOPHYSICS. New York, N.Y., Jan. 29, 29; m. 62. B.S., Yale, 50; Ph.D., M.I.T. 53. Instr. geophysics, M.I.T. 53-54, asst. prof. 54-62. Computer scientist RCA, 57; assoc. prof., geophysics, Mass. Inst. Tech., 62-. Dir. MIT Vela Uniform project 60-. Phi Beta Kappa, Sigma Xi, Amer. Geoph. Union. Geophysics, seismology, time series analysis, digital computer programming, weapon system control.
- TEAGER, Professor Herbert M., ELECTRICAL ENGINEERING, Canton, Ohio, March 20, 30; m. 53; c. 2, S.B., MIT, 52, National Sci. Found fellow, 52-53, Sc.D. (Elec. Eng.), 55. Asst. Elec. Eng., MIT, 53-54, instr., 54-56, Asst. Prof., 59-. Consult., U.S. Navy Bu. of Ships, 59-; Curtiss-Wright Corp., 69-; Inst. Def. Analysis, 61-; American Optical Co., 61-; USNR, 55-59, Lt. Digital computer application and design, particularly man-machine systems, large systems, and control.
- WARD, Dr. John E(rwin), Electronic Systems Laboratory, Massachusetts Institute of Technology, Cambridge, Mass. ELECTRICAL ENGINEERING. Toledo, Ohio, Jan. 4, 20; m. 49, B.S., MIT, 43; M.S., MIT 47. Research staff, MIT Radiation Laboratory 43-45. Research Asst., MIT, 45-47. Staff Member, MIT Div. Sponsored Research, 47-56. Res. Elec. Engineer, MIT, 195-. Project Engineer, Servomechanisms Lab., MIT 49-55. Executive Officer, Servomechanisms Lab., MIT 55-59. Assistant Director, Electronic Systems Laboratory, MIT, 59-. Sigma Xi, Inst. Radio Eng., Assoc. of Comput. Mach. Auto. Control, digital computer applications, radar, weapon fire control, data reduction, instrumentation, man-machine systems.

YNGVE, Dr. Victor H(use), Department of Electrical Engineering, Massachusetts Institute of Technology, Cambridge, Mass. SYMBOLIC PROCESSES. Niagara Falls, N.Y., July 5, 20, m.43, c. 3; B.S. Antioch College, 43, S.M. Univ. Chicago, 1951, Ph.D. (Physics) 1953. Research Asst., cosmic ray research 1947-53, staff member, Res. Lab. of Elec., 1953-54, Asst. Prof. Modern Languages 1954-61, Research Assoc. Elec. Eng. 1961-. Director Mechanical Translation Group 1953-. Consultant, National Bu. of Standards; Editor, Mechanical Translation; President, Assoc. for Machine Translation and Computational Linguistics; Linguistic Society of America, Assoc. for Computing Machinery; American Standards Assoc. Areas of interest: Mechanical translation; Design and construction of programming languages; theory of programming languages; linguistics; machines that understand; information retrieval.

Appendix 4

List of pertinent current research compiled from replies to a questionnaire sent to approximately sixty members of the faculty and research staff.

AUTOMATIC LIBRARIES (Baumann, D. M. B.)

Feasibility study of photographic storage techniques for digital information and weighted area scanning techniques for optical character recognition. Part of a continuing project aimed at developing automatic libraries for scientific and technical information. A high-speed, high-density photographic storage device has been built and another version is nearing completion. An optical character recognition scheme has been simulated on the 7090 and a full-scale reading machine is being designed.

BIOLOGICAL CONTROL SYSTEMS (Stark, L.)

Operation of on-line computer for control systems experiments on neurological systems. Pattern classification studies. Measurement of human estimation of constraints on random processes.

BIOMEDICAL RESEARCH (Rosenblith, W.)

Setting up a New England Center for computer and information technology in the biomedical sciences.

BIOPHYSICAL COMMUNICATIONS (Siebert, W., Rosenblith, W., Morse, H., Peake, W., Goldstein, M., Gerstein, M., Eden, M., Weiss, T.)

Correlation and statistical analyses of electrophysiological data, especially discrete events from single neural units. Development of special purpose analog and digital computers and converters. Simulation of well defined pieces of neural physiological system on the TX-2, especially peripheral parts of the auditory system. Computer recognition of handwriting.

COGNITIVE PROCESSES (Torgerson, W. S., Yntema, B. B., White, B. W.)

Research in the area of complex judgement and decision processes.

COGO PROGRAMMING SYSTEM (Miller, C. L.)

COGO (COordinate GeOmetry) is a programming language and processor for solving geometric problems on a computer. Applicable to computational problems in contour surveys, highway design, right-of-way surveys, interchange design, bridge geometry, subdivision design construction, layout, etc. System is currently being extended and developed as a research tool for man-machine communication.

COMMUNICATION WITH BLIND (Baumann, D. M. B.)

Several studies directed toward improving communication with the blind including design of a high-speed electric Braille and revision of the Braille rules to improve information transfer efficiency.

COMPUTER-AIDED DESIGN (Ross, D., Ward, J., Coons, S., McClintock, F., Kurtz, E., Baumann, D. M. B., Mann, R.)

Investigation of means for facilitating the creative activities in an engineering design process by effecting a symbiosis with the computer. Direct and intimate interaction of man and computer in concept-development and analysis.

COMPUTER-GUIDED DECISION MAKING (Greenberger, M.)

Exploration of management decision processes whose central elements are computer simulations and mathematical decision models run from time-sharing consoles.

CONSOLE DEVELOPMENT (Teager, H.)

Construction of device and programs to accept handwritten input to computer. Development of time-sharing equipment on IBM 7090.

DECISION-MAKING BEHAVIOR (Soelberg, P.)

To study individual and group decision-making behavior under partial uncertainty conflict. Experimental environments have been programmed on computer, which allow systematic variation and laboratory control of stimulus availability, response or alternatives availability, reward structure, complexity of situation, etc.

DESIGN OF COMPUTER SYSTEMS (Lombardi, L.)

Developing a new design philosophy for computer systems based on lists and declarative representation of algorithms. Emphasis on man-machine integration, interaction between independent computers.

GRAPHICAL DISPLAYS ON-LINE (Roberts, L., Gladding, E., Foster, R.)

Development of plotting system on-line with 1620 computer. Application to presentation of computer-generated design information. Use for display of engineering information upon which design decisions can be made.

HEURISTIC PROGRAMS AND SYMBOL MANIPULATION (Minsky, M., Slagle, J.)

Heuristic program to solve symbolic integration problems. Currently writing heuristic program to obtain explicit solutions to differential equations. Several other programs under development.

HUMAN INFORMATION PROCESSES (Torgerson, W. S., Harris, W. P., Mitchell, R. T., Schulman, A. I., Smith, J. E. K., Stowe, A. N., White, B. W., Yntema, B. B., Forgie, J.)

Automatic speech recognition and speaker identification by computers. General research on complex judgement and decision processes (identification, evaluation, memory, and perception) with computer simulation of these processes as their rules are discovered. Man-machine cooperation in decision making.

INDUSTRIAL DYNAMICS (Forrester, J.)

Study by computer simulation of underlying structure and behavior of firms, industries, and economies. Emphasis on interaction of separate elements and on flows of men, materials, money, capital equipment, orders, and information.

INFORMATION PROCESSING SYSTEMS (Carroll, D., Emery, J.)

Study of structure and requirements of information systems in management enterprises, government, and the military.

INFORMATION SYSTEMS LABORATORY (Miller, C. L.)

Civil Engineering Department developing a laboratory facility for student instruction and research in information systems. Being equipped with wide range of electrical, mechanical, optical, and electronic information handling components. Present small computer being provided with facility to communicate with large number of different kinds of input/output devices.

LINGUISTICS STUDIES (Chomsky, N., Halle, M., Mathews, H., Stevens, K.)

Study of restricted infinite automata (bounded memory growth machines, more structured than general Turing machines). Incorporation of grammars into the domain of such machines. Speech sound generation using an electroacoustical analog of the vocal tract driven by computer commands formed from inputs approximating word spellings. Computer verification of and experimentation with hypothetical grammars.

LOGICAL DESIGN (Susskind, A.)

Work on logical design of computers, special purpose computer design, analog-digital conversion techniques, and pulse-circuit design.

MECHANICAL TRANSLATION (Yngve, V.)

Research in methods of mechanizing English and other languages. Study of limited temporary memory on language structure. Improvement and standardization of programming languages (COMIT). Basic research on language and how it carries meaning.

MICROECONOMIC SIMULATION STUDIES (Clarkson, G.)

Simulation of individual decision-making processes, especially as they pertain to economic behavior, using the Complex Information Processing approach of Simon and Newell.

MODELS OF HUMAN OPERATORS (Sheridan, T.)

Research on models of human operator as a control element and as a decision maker in various display-control situations. Also research in programmed instruction.

PATTERN RECOGNITION (Selfridge, O., Neisser, U., Minsky, M.)

Pattern recognition and learning with respect to computer programs. Optimization of programs which assimilate large quantities of data, organize it and search for and recognize significant features in it. Applications to visual recognition problems and to chess. Analysis of nerve networks.

PDP-1 COMPUTER (Dennis, J.)

Time-shared operation for education and research. Work on hardware, consoles, programming, and compilers.

PRIORITY PROBLEM (Greenberger, M.)

In a time-sharing system, the next user to be served is selected on the basis of nature of request, urgency, and time waiting. Such considerations typically lead to conflicts. This study undertakes the resolution of these conflicts through the analysis of mathematical models of priority systems, and the formulation of economic objectives.

RETRIEVAL OF TECHNICAL INFORMATION (Kessler, M.)

Research in the patterns of technical information. Experimental model of a Technical Information System now under development.

SENSORY COMMUNICATIONS (Mason, S.)

Processing of psychophysical data, preparation of punched tapes for control of displays on psychophysical experiments, and computer study of models of sensory communications systems. Research on problems related to sensory aids for blind. Use of computers in unusual picture processing preparatory to coding of visual information for transmission to sense modalities whose capacities are much smaller than that of visual sense.

SOCIAL SCIENCE SIMULATIONS (Pool, I.)

Simulations of election campaign strategies, media-mix reach and frequency, and communication in communist bloc.

SPEECH ANALYSIS AND SYNTHESIS (Dennis, J.)

Use of computer to operate a vocal tract model to synthesize speech, requiring man-machine and machine-equipment interaction.

STRUCTURAL PROGRAMMING SYSTEM (Fenves, S., Logcher, R.)

Research program to develop a language and programming system for analysis and design of structures. Will enable the user to specify in common engineering terms the shape, makeup, and properties of a structure, the loads and other conditions to be investigated, and the type of answers to be produced.

TEACHING MACHINES (Howard, R.)

Research in automatic instruction decision systems; particularly those systems that use a computer as the decision element.

3D INFORMATION STORAGE AND RETRIEVAL (Loeb, A., Robinson, W., Haughton, E.)

Use of algorithms from discrete analytical geometry for the storage, retrieval, and interaction computations of crystal structures. Optimal coding of more general 3-dimensional concepts. Program controlled manipulation of 3-dimensional models applied to concept training in humans by teaching machines.

TIME SERIES ANALYSIS (Simpson, S., Galbraith, J., Claerbout, J.)

High speed storage and retrieval of long time series with associated descriptive material. Programming techniques for ultra-fast computations of correlation functions, spectra, minimum-phase factored spectra, prediction operators, optimum filters, etc. Compilers for automatic subroutine testing and documentation.

VOCODER RESEARCH (Gold, B., Rosen, P.)

Research and development on VOCODERS (band compression devices for speech analysis, band compression, transmission and resynthesis) utilizing special purpose digital computers for determination of pitch and employing digital transmission. Simulation of process on general purpose computers.

Appendix 5

List of One-term MIT Subjects whose 1962-63 Catalogue Descriptions Involve:

X Information Theory, Control Theory, Systems Analysis

XX Specific Mention of Computers or Data Processing Machines

	<u>Subject</u>	<u>Instructor in charge</u>
X	1.03T Social and Political Factors in Engineering	Staff
XX	1.04 Mathematical Methods in Civil Engineering	C. L. Miller
X	1.07, 1.08 Engineering I, II	M. J. Holley
XX	1.15 Computer Approaches to Engineering Problems	P. O. Roberts, C. L. Miller
XX	1.16J Special Studies in Information Systems (A)	C. L. Miller, H. M. Paynter, W. W. Seifert, Y. T. Li
XX	1.19 Engineering of Location (A)	P. O. Roberts
X	1.21 Fundamentals of Transportation Systems (A)	A. J. Bone.
XX	1.212 Transportation Systems Analysis (A)	Staff
XX	1.251 Theory of Traffic Flow (A)	Staff
XX	1.252 Design of Urban Highway Systems (A)	A. J. Bone.
X	1.26 Ground Facilities for Air Transportation (A)	A. J. Bone
XX	1.503 Naval Structural Analysis	R. F. Hansen
XX	1.571, 1.572 Advanced Structural Analysis (A)	J. J. Connor
XX	1.591 Numerical Methods of Structural Analysis (A)	S. J. Fenves
XX	1.951 Construction Management (A)	A. G. Dietz
XX	1.952 Construction Management Seminar (A)	A. G. Dietz
XX	2.00 Introduction to Engineering	H. M. Paynter
XX	2.03 Dynamics	S. H. Crandall
XX	2.215 Methods of Engineering Analysis (A)	S. H. Crandall
XX	2.722 Descriptive Geometry	D. P. Adams
XX	2.723 Elementary Nomography	D. P. Adams
XX	2.724 Nomography	D. P. Adams
XX	2.731 Engineering Design	R. W. Mann
XX	2.732 Design Concepts	D. M. Baumann, H. H. Richardson
XX	2.735 Man-Machine Systems	T. B. Sheridan
XX	2.736 Modern Kinematic Problems	D. P. Adams

Note: (A) Following subject title indicates graduate subject.

<u>Subject</u>	<u>Instructor in charge</u>
XX 2.745J Special Studies in Information Systems (A)	H. M. Paynter, C. L. Miller, W. W. Seifert, Y. T. Li
XX 2.751 Analysis and Design of Engineering Systems I(A)	H. M. Paynter
XX 2.752 Analysis and Design of Engineering Systems II(A)	H. M. Paynter
XX 2.78 Hydraulic and Pneumatic Controls	S. Y. Lee
XX 2.782 Introduction to Automatic Control	J. L. Shearer
XX 2.783 Advanced Automatic Control (A)	J. L. Shearer
XX 2.784 Instruments for Measurement and Control (A)	S. Y. Lee
XX 2.859 Manufacturing Technology	N. H. Cook
XX 4.74 Methods of Research in City Planning (A)	A. Fleisher
X 6.05, 6.053 Circuits, Signals, and Systems	W. M. Siebert
X 6.213 Feedback Control Principles	L. A. Gould
X 6.214 Feedback Control Laboratory	L. A. Gould
XX 6.216 Dynamics of Electric Machines (A, except for Course VI)	C. Kingsley
X 6.232 Electromechanical Control Components	R. H. Frazier
XX 6.25 Digital System Application	H. M. Teager
XX 6.251 Digital Computer Programming Systems	F. J. Corbato
XX 6.252 Digital Systems Engineering	A. K. Susskind, F. C. Hennie
XX 6.27J Probabilistic Systems Analysis	R. A. Howard
X 6.291 Radar-System Engineering	J. F. Reintjes
X 6.311 Principles of Communication	J. M. Wozencraft
X 6.36 Speech Communication	M. Halle, K. Stevens
X 6.37 Sensory Communication	W. Rosenblith, S. J. Mason
XX 6.372 Introduction to Neuroelectric Potentials	M. Goldstein, W. Peake
XX 6.38 Pulse Circuit Analysis	H. J. Zimmermann
X 6.39 Image Transmission Systems	W. Schreiber
XX 6.41 Introduction to Automatic Computation	F. McCarthy
XX 6.533 Algorithms for Optimization and Approximation (A)	A. A. Goldstein
XX 6.536J Systems Engineering and Operations Research (A)	R. A. Howard
XX 6.537 Switching Circuits (A)	D. A. Huffman, E. Arthurs

	<u>Subject</u>	<u>Instructor in charge</u>
XX	6.539 Mathematical Theory of Computation and Artificial Intelligence (A)	F. McCarthy
X	6.54 Sampled and Quantized Systems (A)	R. A. Howard
XX	6.541J Language, Symbolic Processes, and Computers(A)	V. H. Yngve
XX	6.542J Mechanical Translation and Language Processing (A)	V. H. Yngve
XX	6.544J Heuristic Programming (A)	M. L. Minsky
X	6.571 Statistical Theory of Communication (A)	Y. W. Lee
X	6.572 Statistical Theory of Nonlinear Systems (A)	Y. W. Lee
X	6.573 Random Signals and Noise (A)	W. B. Davenport, W. M. Siebert
X	6.574 Transmission of Information (A)	R. M. Fano
X	6.575 Advanced Topics in Information Theory (A)	P. Elias
X	6.576 Statistical Theories of Signal Detection (A)	W. M. Siebert, W. B. Davenport
X	6.59 Bioelectric Signals (A)	W. Rosenblith
XX	6.592 Analytical Models for Human Processing of Sensory Inputs (A)	M. Eden
X	6.595J Biological and Neurological Control Systems(A)	L. Stark
X	6.601 Feedback Control Theory (A)	L. A. Gould
X	6.602 Nonlinear Control Systems (A)	W. W. Seifert
XX	6.604J Special Studies in Information Systems (A)	W. W. Seifert, C. L. Miller, H. M. Paynter Y. T. Li
X	6.606 Control System Synthesis (A)	G. C. Newton
X	6.607 Feedback Control Laboratory (A)	G. C. Newton
X	6.608 Process Control (A)	L. A. Gould
X	6.626 Modulation Theory and Systems (A)	J. M. Wozencraft
X	6.629 Radar System Engineering (RA)	J. F. Reintjes
X	7.595J Biological and Neurological Control Systems(A)	L. Stark
X	7.86 Molecular Genetics (A)	C. Levinthal
X	7.97, 7.98 Molecular Biology Seminar (A)	F. O. Schmitt, P. F. Davison
XX	8.75 Operations Research, Principles and Applications (A)	P. M. Morse, H. P. Galliher, R. A. Howard

	<u>Subject</u>	<u>Instructor in charge</u>
XX	10.34 Numerical Solution of Problems in Chemical Engineering (A)	P. L. Brian
XX	10.35 Dynamics and Control of Chemical Engineering Processes	P. L. Brian
X	10.55 Economic Balance in Chemical Industry(A)	G. C. Williams
X	12.831 Elements of Geophysics I	T. Cantwell, T. Madden
XX	12.851, 12.852 Geophysical Analysis and Computation (A)	S. M. Simpson
XX	13.03 Advanced Hydromechanics of Ship Design	M. A. Abkowitz
XX	13.96 Application of Operational Methods	E. G. Frankel
XX	14.11 Linear and Nonlinear Programming	R. M. Solow
X	14.532 Goals and Strategies in Foreign Affairs	L. P. Bloomfield
X	14.781 Seminar in Learning (A)	Staff
X	14.79T Psychology of Language and Communication	D. H. Howes
X	14.791T Seminar in Psychology of Language and Communication (A)	D. H. Howes
X	14.953 Mass Media and Communication Systems	I. Pool
X	14.954 Methods of Communication Research (A)	F. W. Frey
X	14.956 Public Opinion and Propaganda	I. Pool
X	14.96 Power, Influence and Policy Decisions	F. W. Frey
X	14.771 Seminar on Sensation and Perception (A)	J. A. Swets, D. M. Green
X	15.04 Organization	- -
X	15.092 Mathematics for Industrial Management	M. Greenberger
XX	15.094J Probabilistic Systems Analysis	R. A. Howard
X	15.095 Statistical Decision Theory (A)	R. A. Howard
X	15.12 Management Problems I	H. Hudgins
X	15.51 Industrial Accounting and Control	J. C. Emery
XX	15.542 Management Information Systems (A)	J. C. Emery
XX	15.58 Industrial Dynamics	E. B. Roberts
XX	15.581 Industrial Dynamics I(A)	E. B. Roberts
XX	15.582 Industrial Dynamics II(A)	J. W. Forrester
X	15.592 Mathematical Programming(A)	- -
X	15.593 Stochastic Systems (A)	M. Greenberger
XX	15.594J Systems Engineering and Operations Research (A)	R. A. Howard

	<u>Subject</u>	<u>Instructor in charge</u>
XX	15.599 Research Seminar in Quantitative Analysis (A)	M. Greenberger
X	15.71 Production Management	E. H. Bowman, B. E. Goetz
X	15.72 Industrial Standardization	W. Schreiber
X	15.791 Operational Models of the Firm (A)	- -
X	15.792 Manufacturing Decisions Seminar (A)	E. H. Bowman
XX	15.82 Marketing Management	H. J. Claycamp
XX	15.821 Marketing Policy and Administration (A)	G. B. Tallman
X	15.83 Marketing Research	R. B. Maffei
XX	15.832 Demand Analysis and Marketing Research(A)	R. B. Maffei, R. M. Cunningham
X	15.92 Organization (A)	- -
X	16.30 Principles of Automatic Control	W. McKay
X	16.31 Principles of Instrumentation and Control(A)	Y. T. Li
X	16.32 Principles of Instrumentation and Control(A)	Y. T. Li
XX	16.33 Automatic Control Systems Lab.(A)	Y. T. Li
XX	16.362J Special Studies in Information Systems(A)	Y. T. Li, C. L. Miller, H. M. Paynter, W. W. Seifert
X	16.37 Statistical Problems in Automatic Control(A)	W. W. Vander Velde
X	16.38 Physical Components of Control Systems (A)	R. K. Mueller
X	16.40 Control Systems Principles	H. P. Whitaker
X	16.41T Control System Engineering (A)	J. Hovorka
X	16.42 Weapons Systems (RA)	W. Wrigley, W. R. Markey
X	16.43 Weapons Systems Lab (RA)	R. K. Mueller
X	16.44 Automatic Control of Flight Vehicles (A)	H. P. Whitaker
X	16.46 Astronautical Guidance (A)	R. H. Battin
XX	16.74T Advanced Flight Vehicle Engineering (A)	R. H. Miller, M. A. Hoffman
X	16.761, 16.762 Orbital and Ballistic Flight (A)	P. E. Sandorff, M. A. Hoffman
X	16.78 Control and Guidance in Flight Transportation (A)	H. P. Whitaker

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	<u>Subject</u>	<u>Instructor in charge</u>
X	18.11 Operations Research (A)	G. P. Wadsworth
XX	18.16J Heuristic Programming and Artificial Intelligence (A)	M. L. Minsky
X	18.80 Topics in Foundations of Math.(A)	H. Rogers
X	19.34 Statistical Methods in Meteorology	E. N. Lorenz
X	19.35 Statistical Problems in Meteorology	E. N. Lorenz
XX	19.46 Numerical Weather Prediction (A)	N. A. Phillips
XX	19.67 Planetary Fluid Dynamics (A)	J. G. Charney
X	22.241 Principles of Control Systems(A)	E. Gyftopoulos
XX	22.242 Nuclear Plant Dynamics (A)	E. Gyftopoulos
XX	22.26 Nuclear Reactor Design (A)	H. Fenech
XX	22.53T Digital Computers in Nuclear Engineering(A)	K. F. Hansen
XX	22.531 Digital Computers in Nuclear Engineering(A)	K. F. Hansen
X	23.751 Language and Society	M. Halle
XX	23.771 Mathematical Backgrounds for Communications Sciences	B. Hall
XX	23.772 Mathematical Models in Linguistics	N. Chomsky
XX	23.791J Language, Symbolic Processes, and Computers (A)	V. H. Yngve
XX	23.792J Mechanical Translation and Language Processing (A)	V. H. Yngve

APPENDIX 3

